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STELLA-II: Staged Monoenergetic Laser Acceleration – Experiment Update

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Abstract. The goal of STELLA-II is to demonstrate staged monoenergetic laser acceleration of microbunches using an inverse free electron laser (IFEL) buncher and IFEL accelerator. A key feature of this experiment is the usage of a single high-intensity laser beam to simultaneously drive both the buncher and accelerator. A chicane between the buncher and accelerator causes microbunches to form at the entrance to the accelerator. All hardware has been installed at the Accelerator Test Facility (ATF) located at Brookhaven National Laboratory, including a new laser beam transport system to permit delivering higher laser power. Preliminary test results indicate that modulation and acceleration of the microbunches are occurring with the new system. Energy gains >13% have been observed. Current experiments are being conducted with the ATF CO_2 laser operating at a pulse length of ~180 ps. In late autumn 2002, the ATF CO_2 laser will be upgraded to produce pulse lengths of <10 ps at approximately the same output pulse energy. This higher peak power will enable higher acceleration and more complete trapping of the laser-generated microbunches in the accelerator. This higher acceleration and trapping will also result in a clean separation of the accelerated microbunch electrons from the unaccelerated ones while at the same time maintaining a narrow energy spread.

INTRODUCTION

The development of practical linacs based upon laser acceleration mechanisms will require staging the process multiple times in order to obtain high net energy gain [1]. Moreover, it is critical during the staging process that the accelerated electrons remain grouped tightly together as a microbunch(es) with narrow energy and phase spread. The former attribute we refer to as being monoenergetic and the latter represents maintaining a short bunch length in longitudinal space. Thus, useful staging requires more than resynchronizing the microbunches with the accelerating wave in each stage; it must also be done in a manner that does not degrade the microbunch qualities.

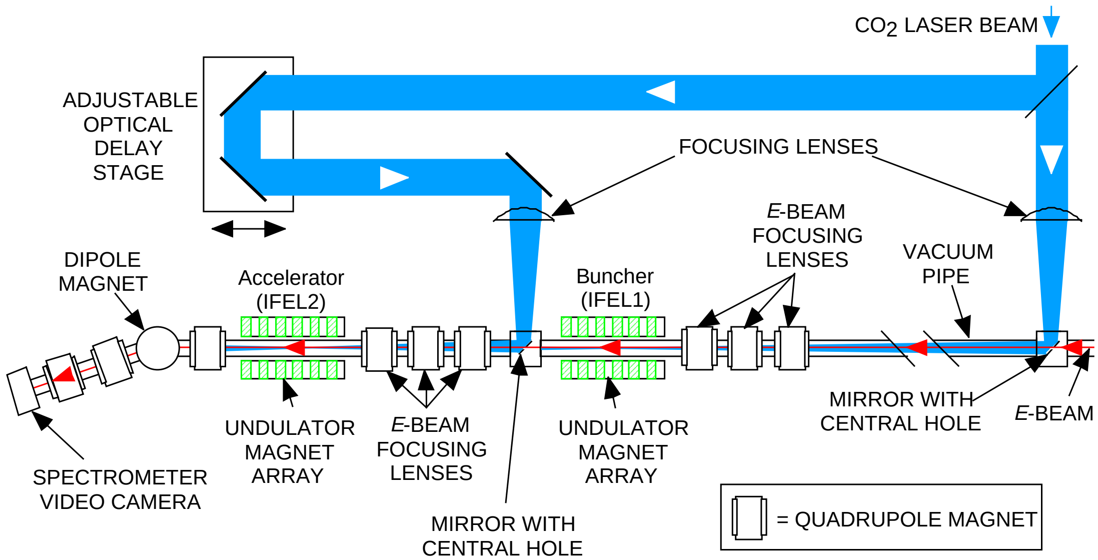


FIGURE 1. Schematic layout for the first STELLA experiment where staging was first demonstrated.

The Staged Electron Laser Acceleration (STELLA) experiment demonstrated the basic staging process using two inverse free electron lasers (IFEL) [2]. A schematic layout of this experiment is shown in Fig. 1. The output from the ATF CO_2 laser is split into two beams – the first beam is focused into the first undulator (IFEL1), which serves as a buncher, and the second beam is sent to a delay stage and then focused into the second undulator (IFEL2), which acts as the accelerator. The purpose of the buncher is to modulate the *e*-beam energy. This leads to the formation of ~3-fs long microbunches at the accelerator located 2 m downstream of the buncher. By adjusting the phase delay we demonstrated the ability to resynchronize the microbunches with the laser light driving the accelerator.

STELLA-II builds upon the success of these first experiments. The primary goal of STELLA-II is to demonstrate monoenergetic acceleration of the microbunches. To do this requires separating the microbunches in energy from the unaccelerated background electrons and trapping the microbunches in the laser beam ponderomotive potential well. This separation implies the need to impart significant energy gain on the microbunches. Thus, key differences between the first STELLA experiment and STELLA-II is utilizing higher laser power from an upgraded ATF CO_2 laser and using a tapered undulator for IFEL2.

Another key feature of STELLA-II is using a single laser beam to drive both the buncher and accelerator. This greatly reduces phase jitter between the two devices and allows minimizing the separation distance between the buncher and accelerator by using a chicane rather than a drift space. The laser beam transport system was also modified to withstand the much higher laser pulse energy from the upgraded laser. Figure 2 gives a schematic layout for the STELLA-II experiment.

All the major hardware components have been delivered to the ATF. This includes two different bunchers [an electromagnet (EM) and a fixed-gap permanent-magnet

(PM) device], a hybrid PM/EM chicane, and two undulators (untapered and tapered). These devices are described below and preliminary results are presented.

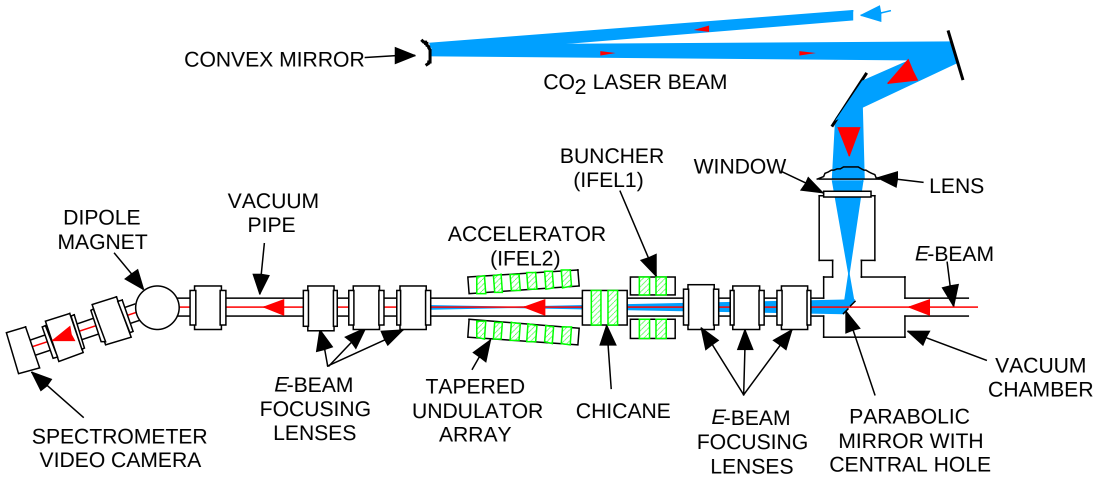


FIGURE 2. Schematic layout for the STELLA-II experiment.

DESCRIPTION OF HARDWARE AND SYSTEMS

Laser Beam Transport System

The ATF laser presently delivers approximately 5-J laser pulses with 180-ps pulse length. Once upgraded the laser will deliver about the same amount of pulse energy, but the pulse length will be <10 ps. To transport this amount of pulse energy, the laser beam diameter must be large enough to keep the fluence on the optics below their damage threshold, in particular on any transmissive optics, which tend to have much lower damage limits than metal mirrors. Consequently, metal mirrors are used wherever possible; however, a window is still needed on the *e*-beam vacuum pipe to permit transmission of the laser beam. Thus, one requirement of the laser beam transport design is to position this window where the laser beam has a large size.

Another requirement is to focus the laser beam in the center of the accelerator (IFEL2) as tightly as possible to maximize the laser intensity. This implies the need for a short Rayleigh range, which means the vacuum pipe upstream of IFEL2 must increase in diameter to accommodate the rapidly expanding laser beam. A triplet located immediately upstream of the buncher (see Fig. 2) limits the maximum size of the laser beam; however, it is large enough to provide the short Rayleigh range desired for the experiment. Nonetheless, at this point in the laser beam transport the beam is still too small for the beamline window. Hence, there was a need to further expand the laser beam size.

To solve this problem, we use a NaCl lens positioned just before the beamline window and a 90° off-axis parabolic mirror as depicted in Fig. 2. The combination of the lens and parabolic mirror provides both the short Rayleigh range and large beam size at the window. Although this scheme has an internal focus, this focus occurs within the beamline vacuum.

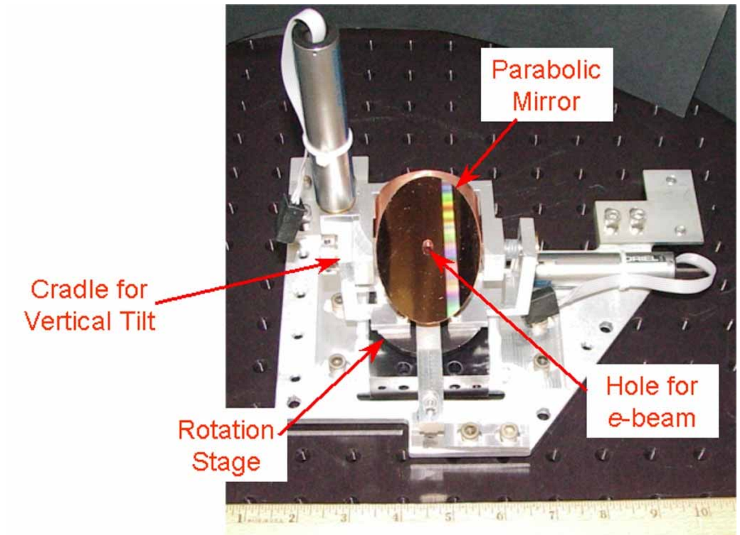


FIGURE 3. Photograph of 90° off-axis parabolic mirror on remote-controlled cradle.

Figure 3 is a photograph of the parabolic copper mirror, which has a 4-mm dia. hole drilled through its center for transmission of the *e*-beam. The mirror is supported on a vacuum-compatible, remotely adjustable cradle that provides both vertical and horizontal tilt control.

Bunchers

A photograph of the EM buncher is shown in Fig. 4. It is a 3-pole device with field clamps on its ends to control the magnet field distribution. It is also designed to be slightly off resonance. These attributes enable it to modulate the *e*-beam by only a small amount (~±0.4%) despite being driven by very high laser peak power. Due to the short Rayleigh range, the laser intensity inside the buncher is also small.

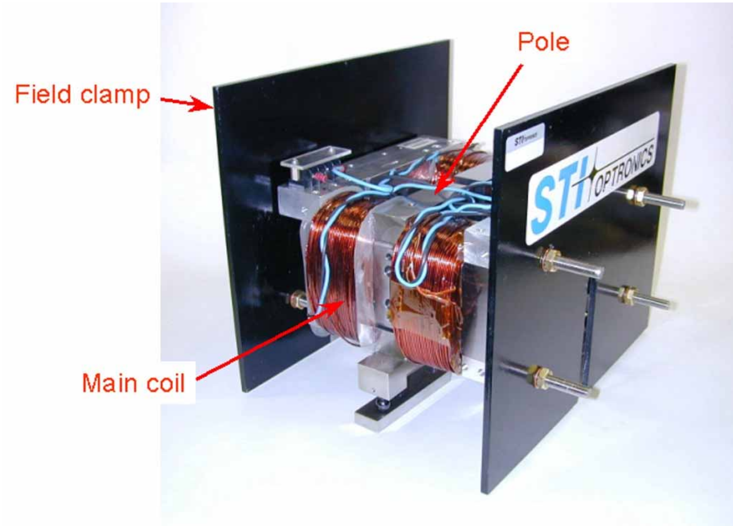


FIGURE 4. Photograph of EM buncher.

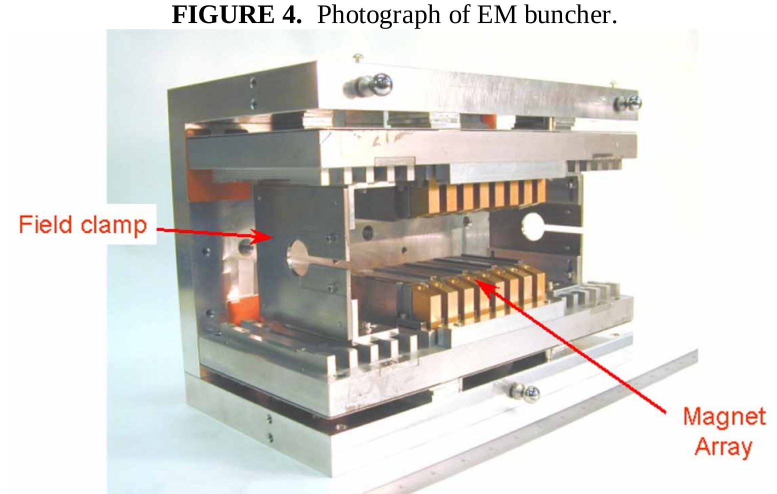


FIGURE 5. Photograph of PM buncher lying on its side to show the gap.

The PM buncher, shown in Fig. 5, is a 5-period device designed to be on-resonance for a 45.6 MeV *e*-beam. This permits it to operate at lower laser intensities despite having a large gap. Field clamps are located inside the C-frame, which is the same basic design as for the undulators used in IFEL2.

Chicane

The chicane (see Fig. 6) uses a 3-pole PM configuration to convert the energy modulation to density modulation. It has been pretuned assuming ±0.4% modulation by the buncher. Using the main coil to change the magnetic field about this nominal point controls when the microbunches arrive in phase relative to the laser light in the accelerator. Energizing this main coil also causes deflection of the *e*-beam, which can be compensated using trim coils on the ends of the chicane. The magnetic field of the chicane is oriented orthogonal to the buncher and the tapered undulator to minimize *e*-beam interaction with the laser beam inside the chicane.

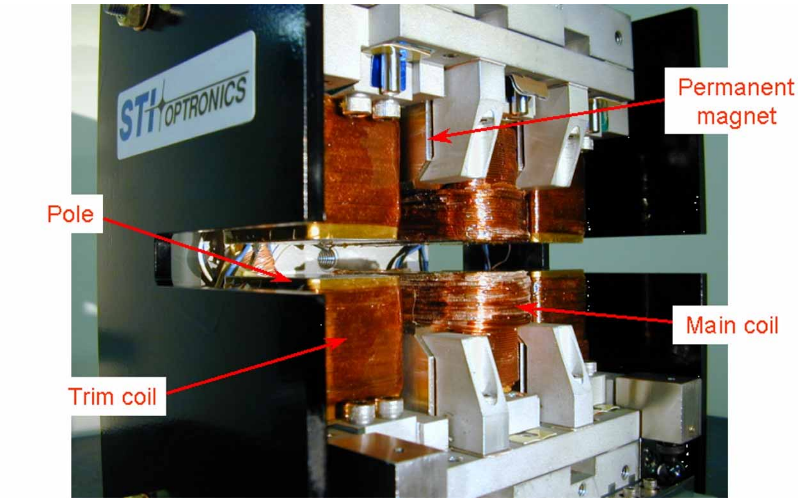


FIGURE 6. Photograph of hybrid PM/EM chicane.

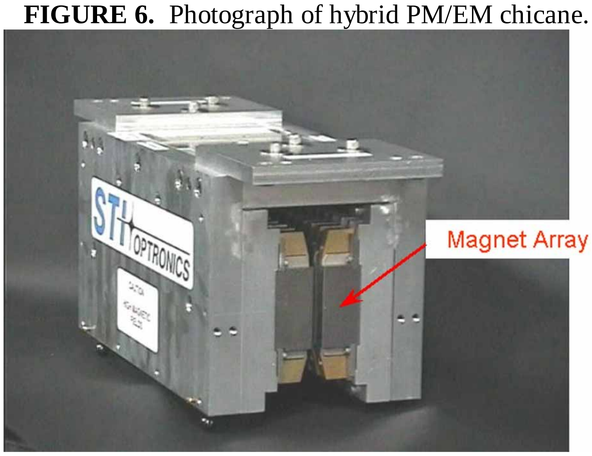


FIGURE 7. Photograph of tapered undulator.

Tapered Undulator

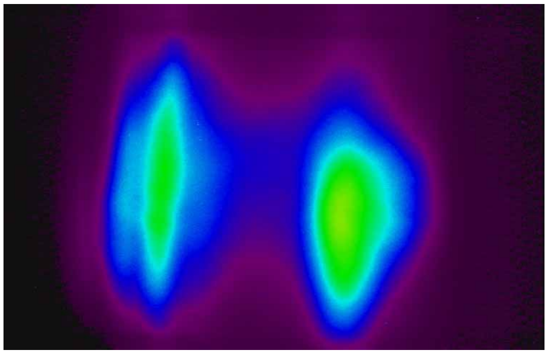
Figure 7 is a photograph of the tapered undulator. It is the same undulator used during the first STELLA experiment [3] except with one end of the magnet array tapered to smaller gap. Presently the gap taper is set at 8%; it is capable of a maximum taper of ≈19%.

PRELIMINARY RESULTS

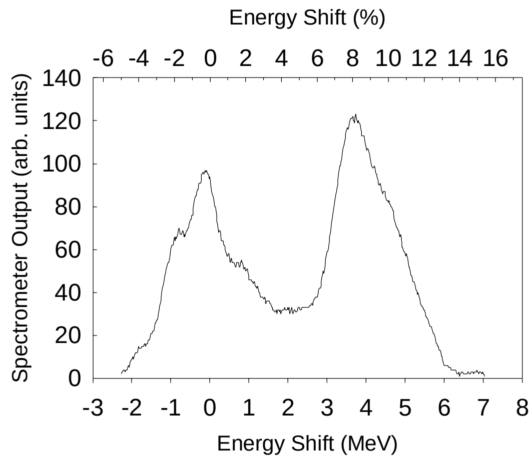
Initial tests indicate the PM buncher is undermodulating the *e*-beam by producing a modulation of only roughly ±0.2% instead of the needed ±0.4%. This implies the laser intensity within the buncher is lower than expected. Recall due to the short Rayleigh range, the laser beam diameter at the buncher is large (>1 cm). Nonuniformities in the intensity distribution can lead to weaker modulation. Such nonuniformities might be caused by diffraction effects due to, say, the central hole in the parabolic mirror. Further tests and analysis will be conducted to understand the cause for the smaller modulation.

The STELLA-II experiment can still be performed since the weaker modulation only results in less tightly bunched electrons. Figure 8 shows preliminary raw data from the electron energy spectrometer as a function of the chicane phase delay. Figures 8(a), (c), and (e) are the spectrometer video camera images where energy increases to the right. Figure 8(b), (d), and (f) are the energy profiles through the center of these images. We have arbitrarily assigned 0° phase to Fig. 8(c), which showed the maximum acceleration for this particular set of data. Indeed, a maximum acceleration of >13% was measured, which to our knowledge is the largest amount of acceleration observed from an IFEL thus far.

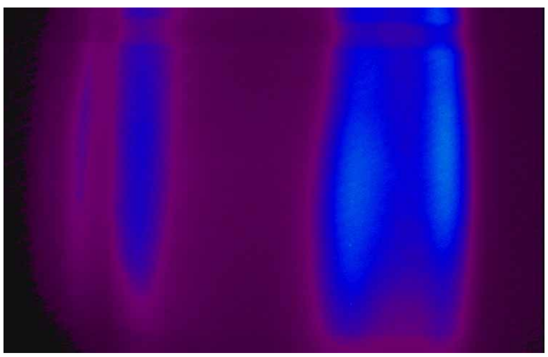
As the phase delay is adjusted ±100° from Fig. 8(c), we see evidence that a group of electrons is shifting in energy. The energy peaks are quite broad, which is consistent with nonoptimal bunching of the electrons due to the undermodulation by



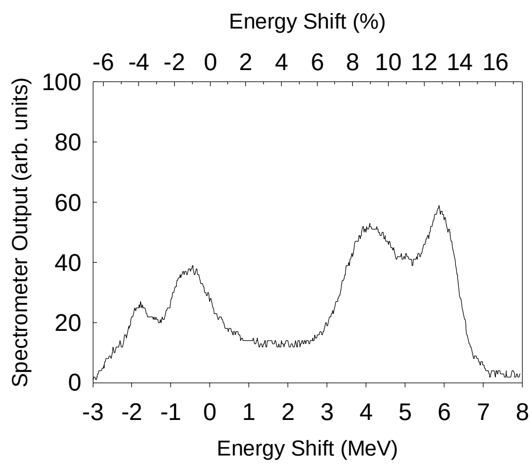
(a) Phase delay = -100°



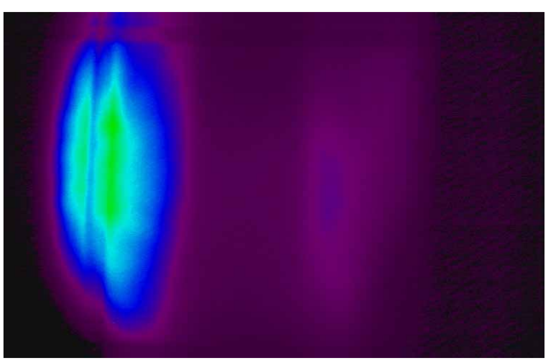
(b)



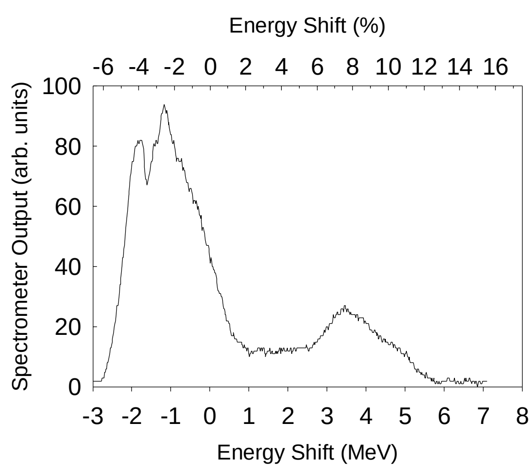
(c) Phase delay = 0°



(d)



(e) Phase delay = +100°



(f)

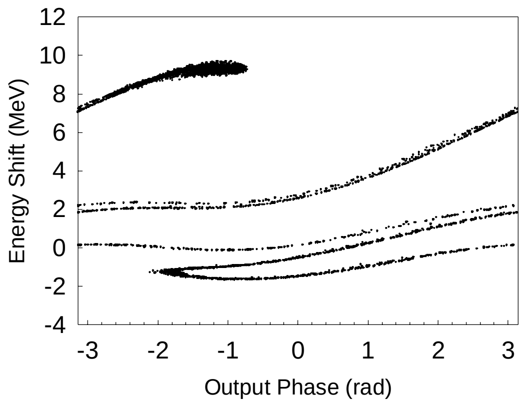
FIGURE 8. Preliminary experimental results for STELLA-II. (a), (c), and (e) are raw video output from the spectrometer camera with energy dispersion increasing to the right. (b), (d), and (f) are line profiles through the center of (a), (c), and (e), respectively.

the buncher. Hence, this preliminary data seems to indicate that the chicane is functioning properly.

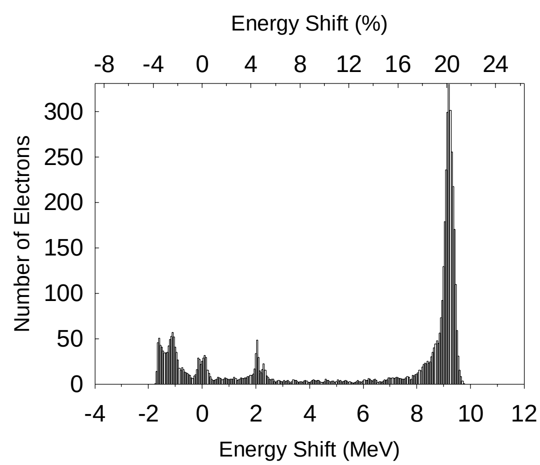
Even with 13% energy gain, this preliminary data shows that the microbunch electrons have not gained enough energy to separate from the background electrons. As shown below, our model predicts at least 20% energy gain will be necessary for this separation to occur. This requires setting the accelerator undulator to 19% gap taper since the amount of energy gain is directly related to the amount of taper. A larger taper also requires higher laser intensity to drive it. All this points to the need for the upgraded CO_2 laser, which should provide more than enough peak power to drive a 19% gap tapered undulator and the EM buncher rather than the PM buncher.

MODEL PREDICTIONS FOR UPGRADED LASER

Assuming a 19% gap tapered undulator and the upgraded CO_2 laser with 1 TW/cm^2 at the center of the undulator, Fig. 9 gives the model predictions for the STELLA-II experiment. The chicane phase has been adjusted for minimum energy spread of the microbunch and a high resolution spectrometer is assumed.



(a)



(b)

FIGURE 9. Model predictions for STELLA-II using upgraded ATF CO_2 laser. (a) Energy-phase diagram. (b) Energy histogram.

This shows in Fig. 9(a) the microbunch electrons trapped in a fairly small group (see upper left-hand corner of phase diagram). These electrons have a narrow energy spread as seen in Fig. 9(b) and are well separated from the background electrons. Note, the energy gain is 20%.

CONCLUSIONS

The STELLA-II experiment has begun obtaining its first data. An energy gain >13% has already been observed. Complete energy separation of the trapped microbunches from the background electrons requires an energy gain of at least 20%. To achieve this requires utilizing the higher laser peak power that will be available from the upgraded ATF CO_2 laser and a 19% gap-tapered undulator. This upgrade should be completed by the end of 2002 at which point the STELLA-II primary goal of demonstrating staged monoenergetic laser acceleration can be achieved. In the meantime, the experiment will be operated at lower laser power in order to further characterize and optimize the equipment.

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REFERENCES

1. P. Sprangle, "Laser Driven Plasma Accelerators," in these Proceedings.
2. W. D. Kimura, A. van Steenbergen, M. Babzien, I. Ben-Zvi, L. P. Campbell, C. E. Dilley, D. B. Cline, J. C. Gallardo, S. C. Gottschalk, P. He, K. P. Kusche, Y. Liu, R. H. Pantell, I. V. Pogorelsky, D. C. Quimby, J. Skaritka, L.C. Steinhauer, and V. Yakimenko, Phys. Rev. Lett. **86**, 4041-4043 (2001).
3. W. D. Kimura, L. P. Campbell, C. E. Dilley, S. C. Gottschalk, D. C. Quimby, A. van Steenbergen, M. Babzian, I. Ben-Zvi, J. C. Gallardo, K. P. Kusche, I. V. Pogorelsky, J. Skaritka, V. Yakimenko, D. B. Cline, P. He, Y. Liu, L. C. Steinhauer, and R. H. Pantell, Phys. Rev. ST Accel. Beams, **4**, 101301 (2001).